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Quantum Transport, Noise and Non-Linear Dissipative Effects
in One- and Two-Dimensional Systems and
Associated Sub-Micron and Nanostructure Devices

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Summary of Work Accomplished

The underlying theme of most of our research has been transport and noise phenomena in sub-micron systems and devices. This subject is of interest for both basic and technological reasons and it is now well-recognized that many interesting quantum phenomena come into play in the so-called mesoscopic regime. Whereas in the past we placed emphasis on the development of optimum techniques, our present thrust has been geared toward applications of same.

The main thrust of the research was concerned with semiconductor quantum wires and special emphasis was placed on analyzing the relevant experiments. In recent years the study of lightly doped semiconductor quantum wires has attracted much attention. A quantum wire is defined here to have a very narrow width $W \sim \lambda_F$ (Fermi wavelength) so that the electron states are essentially quantised laterally. In this way it is different from both the usual effective one-dimensional (1D) system where $W \gg \lambda_F$ (no lateral quantisation), and the strictly 1D systems where there is no lateral degree of freedom. Such systems are referred to as quasi-one-dimensional (Q1D) systems, where many novel effects have been detected with exciting possibilities for device applications.

Our initial work was concerned with the effect of an electric field on weak localization in a semiconductor quantum wire (publication nos. 1 and 4 on the attached list). We made use of our generalized quantum Langevin equation approach to the conductivity problem. Our theory explains well the recent experiments of Hiramoto *et al.* (Appl. Phys. Lett. 54, 2103 (1989)) who found temperature independent transport behaviour at very low temperature for narrow AlGaAs/GaAs quantum wires, and especially

gives a very good fit to the conductivity data extracted from their experiments.

Next, we commenced a study of electron-electron interactions in Q1D systems. It is known that the Coulomb interaction of the electrons in a strictly 1D system ("strictly" referring to the fact that there exists only one energy band) has a logarithmic divergent behavior in the long-wavelength limit ($q \rightarrow 0$). For a Q1D system, due to the lateral quantization, the occupation of many subbands is possible, and extra terms such as the intersubband Coulomb interaction emerge. The form of the Coulomb interaction is quite complicated and is generally evaluated numerically both for the intrasubband and intersubband cases (with the ground-state intrasubband Coulomb interaction as the only analytical case appearing in the literature).

The large amount of numerical work involved in evaluating the Coulomb interaction not only constitutes an obstacle to setting up a practical transport theory for the Q1D system, but also gives no hint of the answer to some basic physical questions, such as the difference between the intrasubband and intersubband interactions. Therefore it is very desirable to find a simple form for the Q1D Coulomb potential matrix elements. This is what we accomplished in Publ. no. 5. This was the basis for our calculation (no. 6) of the dielectric response of a Q1D system which was then used to study impurity screening and plasmon excitations in the presence of multi-subbands. Finally, we were able to provide an explanation for the experimental results of Hansen *et al.* (Phys. Rev. Lett. 58, 2586 (1987)) concerning the relationship between the inter-subband plasmon frequencies and the electron densities. More detailed studies of intersubband plasmons in semiconductor quantum wires were carried out

in nos. 9 and 17 and detailed and satisfactory comparisons were made with the experiment work of Hansen *et al.* and Brinkop *et al.* (Phys. Rev. B 37, 6547 (1988)).

In no. 12, we calculated the acoustic-phonon-limited low temperature mobility for a quasi-one-dimensional semiconductor quantum wire with multi-populated subbands at finite temperature. Our results show that the acoustic phonon-limited relaxation rate has a temperature dependence of $T^n(T)$, with $0 < n(T) < 2$, and the lower the temperature the larger the $n(T)$ value. Also, in the typical experimental temperature range ($1 < T < 10$ K) for the semiconductor quantum wire, $n \sim 1$. In studying the density dependence, we find that whenever the Fermi velocity of the electrons in the top populated subbands is close to the sound velocity the phonon-limited relaxation rate reaches peak values which also increase with the increasing electron density. These predictions remain to be tested experimentally.

Our final study of semi-conductor quantum wires (no. 11) was concerned with subband effects on electron transport. This work was motivated by recent experiments which used multiple parallel quantum wires since such systems display negligible phase-coherent effects and so leave the subband effects as the dominant quantum phenomenon. Thus, our goal was to develop a systematic transport theory for the Q1D system where the phase-coherence effects are negligible, and to give a firm account of the subband effects on the Drude conductance. For a comprehensive study of the transport properties, one has to confront the intrinsic problems of the Q1D electronic behavior that arise from the low dimensionality and the lateral quantization, on the one hand, and to find a transport theory which is suitable for the Q1D systems, on the other hand.

We succeeded in this endeavor. In particular, we demonstrated that at $T = 0$ the free electron model is inadequate for the study of Q1D transport. However, we show also that the sharp drop of the dc conductance due to the subband effect is greatly smoothed by the combined effects of the broadening and screening due to the electron-electron interactions. Our theory is in qualitative agreement with results from the recent experiment of Ismail *et al.* (J. Vac. Sci. Technol. B 7, 2025 (1989)). We expect even better agreement when we take into account the fluctuating widths of the wires, as we noted in a preliminary presentation (no. 21).

Turning next to questions of noise in lower-dimensional systems, in no. 3 we carried out a detailed analysis of $1/f$ noise within the framework of a nonlinear-generalized-Langevin equation approach. Based on a model of fluctuating hydrodynamics (which was previously developed for this purpose in no. 2) we derived a formula for the frequency dependence of the excess noise. In particular, the excess-noise formula which we obtained for a two-dimensional system agrees with the well-known empirical Hooge formula, and the theoretical form of the Hooge parameter we obtained is consistent with the known experimental results. As our calculations are based on the very general nonlinear Langevin equation, the results we obtained support the thesis that the $1/f$ noise is a universal property and they explain why the empirical Hooge formula works so well for such a variety of materials.

All of the above work was carried out in collaboration with my Post-Doc, G. Y. Hu. Also, our work through summer 1990 is reviewed as part of an invited presentation which I made at a NATO Advanced Study Institute (no. 10).

Another collaboration involved my student, X. Li, and my long-time collaborator from the University of Michigan, G. W. Ford, an investigation was carried out on magnetic field effects (nos. 7 and 8) in dissipative systems. One result which emerged is that, in contrast to its effect on conductivity formulae, a magnetic field does not affect noise properties.

Ford and I also realized that our work on the generalized Langevin equation in essence provided us with the machinery to solve a classic problem in electrodynamics viz. the case of a radiating electron, whose equation of motion has to contain a radiation reaction contribution. This is a very precisely posed problem and we were excited to obtain (no. 13) an equation which is much simpler than that of Abraham-Lorentz (in the sense that it only contains first and second derivatives whereas the Abraham-Lorentz equation contains third derivatives) and yet does not contain the well-known problems associated with the latter (as discussed in Jackson and numerous books). This in turn led us to propose a modification to the Larmor formula (nos. 14 and 15). While the results are very interesting per se we also feel that they give strong vindication of the general techniques which we have developed and are now using in the condensed-matter arena.

Finally, motivated by my recent interest in Single Electronics (Coulomb blockade etc., which involves tunneling in a dissipative environment), in collaboration with Ford and Lewis, I considered some general but important questions of principle. In particular, it is generally considered that for a so-called normal system dissipation decreases tunneling rates. However, we were able to show that at least one example of a normal heat bath, the blackbody radiation field, leads to an increase in tunneling (no. 16). The reason for this exception to the general rule is the

presence of mass renormalization. What has gone wrong with the earlier proofs that normal dissipation always causes decreased tunneling? The point is that it was considered that dissipation corresponds to the presence of the memory term $\mu(t)$ in the quantum Langevin equation and that no dissipation corresponds to setting $\mu(t)$ equal to zero. In the blackbody case this would correspond to defining dissipationless tunneling in terms of the bare mass m . But the bare mass is unobservable: the observed mass is the renormalized mass M and this is what should appear in the definition of dissipationless tunneling. The point here is that the coupling to the radiation field has two kinds of effects: a dynamical effect, corresponding to an electromagnetic contribution to the mass, and a dissipative effect, corresponding to radiation reaction. Both effects appear in the memory term $\mu(t)$.

In summary, the bulk of our research has been concerned with transport and noise properties of lower-dimensional systems. The thrust of our work was concentrated on semi-conductor quantum wires and a variety of phenomena were investigated and compared successfully with many different experiments. The usefulness and universality of the techniques which we used was also demonstrated by the intriguing results we obtained in connection with a classical problem (relating to radiation reaction) in electrodynamics. Finally, some insight of a general nature was gained in the area of dissipative quantum tunneling.

Graduate Students Supported under the Grant

Postdoctorals Supported under the Grant

Gen-you Hu. He has been working with me since May 1986 and is still working with me.

Papers Published in Refereed Journals/Books

1. G. Y. Hu and R. F. O'Connell, "Electric Field Effect on Weak Localization in a Semiconductor Quantum Wire," Proc. of the Sixth International Conference on Hot Carriers in Semiconductors, Scottsdale, Arizona, July 1989, Solid State Electronics 32, 1253 (1989).
2. G.Y. Hu and R.F. O'Connell, "Two-Dimensional Brownian Motion and Fluctuating Hydrodynamics", Physica A 163, 804 (1990).
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4. G. Y. Hu and R. F. O'Connell, "Weak Localization Theory for Lightly Doped Semiconductor Quantum Wires," J. Phys.: Condens. Matter 2, 5335 (1990).
5. G. Y. Hu and R. F. O'Connell, "Electron-Electron Interactions in Quasi-One-Dimensional Electron Systems," Phys. Rev. B 42, 1290 (1990).
6. G. Y. Hu and R. F. O'Connell, "Dielectric Response of a Quasi-One-Dimensional Electron System," J. Phys.: Condens. Matter 2, 1 (1990).
7. X. L. Li, G. W. Ford and R. F. O'Connell, "Magnetic Field Effects on the Motion of a Charged Particle in a Heat Bath," Phys. Rev. A 41, 5287 (1990).
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9. G. Y. Hu and R. F. O'Connell, "Intersubband Plasmons in Quasi-One-Dimensional Systems," in Nanostructures: Fabrication and Physics, edited by S. D. Berger, H. G. Craighead, D. Kern and T. P. Smith III (Materials Research Society, 1990).
10. R. F. O'Connell and G. Y. Hu, "The Few-Body Problem in Nanoelectronics," Invited paper, presented at a NATO Advanced Study Institute, Il Ciocco, Italy, July 23-August 4, 1990, in Physics of Granular Nanoelectronics, edited by D. K. Ferry, J. Barker and C. Jacobini (Plenum Press, 1991).
11. G. Y. Hu and R. F. O'Connell, "Subband Effects on Electron Transport in Quasi-One-Dimensional Electron Systems," Phys. Rev. B 43, 12341 (1991).
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13. G. W. Ford and R. F. O'Connell, "Radiation Reaction in Electrodynamics and the Elimination of Runaway Solutions," Phys. Lett. A 157, 217 (1991).
14. G. W. Ford and R. F. O'Connell, "Total Power Radiated by an Accelerated Charge," Phys. Lett. A 158, 31 (1991).
15. G. W. Ford and R. F. O'Connell, "Structure Effects on the Radiation Emitted from an Electron," Phys. Rev. A 44, 6386 (1991).
16. G. W. Ford, J. T. Lewis and R. F. O'Connell, "Quantum Tunneling in a Blackbody Radiation Field," Phys. Lett. A 158, 367 (1991).
17. G. Y. Hu and R. F. O'Connell, "Intersubband Plasmons in Semiconductor Quantum Wires," Phys. Rev. B 44, 3140 (1991).

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18. G. Y. Hu and R. F. O'Connell, "Electron-Electron Interactions in Quasi-One-Dimensional Electron Systems," Bull. Am. Phys. Soc. 35 (3), 768 (1990).
19. R. F. O'Connell and G. Y. Hu, "Transport in Semiconductor Quantum Wires: Weak Localization and High Field Effects," Bull. Am. Phys. Soc. 35 (3), 641 (1990).
20. R. F. O'Connell and G. Y. Hu, "Subband Effects on Electron Transport in Quasi-One-Dimensional Electron Systems," Bull. Am. Phys. Soc. 36 (3), 411 (1991).
21. G. Y. Hu and R. F. O'Connell, "Strong Localization in Semiconductor Quantum Wires," Bull. Am. Phys. Soc. 36 (3), 926-927 (1991).

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22. R. F. O'Connell and G. Y. Hu, "Low Voltage Resistance in Small Josephson Junctions," Bull. Am. Phys. Soc., to appear.
23. G. Y. Hu and R. F. O'Connell, "On Deviations from the Ambegaokar-Baratoff Critical Current for Small Josephson Junctions," Bull. Am. Phys. Soc., to appear.